

WIRELESS, BATTERY-POWERED COATING HEALTH MONITOR (CHM)

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ABSTRACT

A coating health monitor (CHM) is based on electrochemical impedance spectroscopy (EIS). It consists of a mini-potentiostat coupled to electrodes mounted on top of a paint coating. It is periodically interrogated by a laptop so an inspector can assess the paint's condition and determine if detailed inspection or maintenance is needed. The units are battery powered with an estimated battery lifetime of up to ten years, depending on the frequency of measurement and interrogation. CHMs can be strategically placed in areas difficult to access, monitor, and maintain. These wireless units can be read up to 500 feet away by a laptop that displays the current coating condition. Benefits include increased readiness and safety and reduced inspection costs.

Several panels with different paint coatings were tested in the laboratory. Accelerated corrosion exposure was achieved with alternate immersion. EIS measurements for the CHM and a commercial potentiostat exhibit excellent agreement over six orders of magnitude. The good coatings exhibit high electrochemical impedance with very little change during testing. No corrosion was seen after 90 days. In contrast, although poor coatings exhibited high initial impedance, their impedance had dropped by several orders of magnitude by the first measurement period and rust quickly appeared.

INTRODUCTION

Corrosion is a wide-spread problem that affects nearly all industry and government sectors. A recent report determined that the direct cost of corrosion in the United States to be 3.1% of the Gross Domestic product (GDP).¹ This corresponds to \$300B annually or \$1000 per person. This figure includes only the *direct* costs (e.g., corrosion prevention, corrosion inspection, and replacement or refurbishment of

corroded structures). The *indirect* costs (e.g., lost productivity, taxes, and overhead) were conservatively estimated to be equal to the direct costs.

The annual cost of corrosion in the Department of Defense is estimated to be \$22.5B² and represents 23% of all DoD maintenance costs. The Navy is especially susceptible to corrosion because the marine environment is one of the most corrosive natural environments on earth. The estimates of Navy's share of the costs of corrosion range up to \$6.6B.^{2,3,4} The indirect costs of corrosion, including loss of readiness, decreased safety, and even loss of life, can be even more significant to DoD, especially in times of conflict. To combat corrosion, a variety of approaches are possible: material selection, coatings, environment modification (e.g., adding inhibitors), cathodic protection, etc. None of these approaches are perfect and their effectiveness in preventing or slowing corrosion can decrease over time or can be compromised by mechanical damage or other episodic events. Monitoring or inspecting the effectiveness of corrosion protection and control (CPC) is highly desired for critical equipment or structures.

Paint coatings are the primary means of corrosion protection for most structures and they can be very effective. However, paint coatings are only temporary; they weather, absorb moisture, blister, become scratched or undergo other mechanical damage. Even fresh paint coatings can exhibit pinholes, holidays, or other coating defects that can adversely affect corrosion protection. Thus, there is a need for corrosion sensors to assess the health and effectiveness of paint coatings, especially on critical structures and equipment.

Many corrosion sensors have been proposed and developed,^{5- 12} and several have been recently reviewed by Scully.¹³ However, many of these are not suitable for monitoring coating health. A major disadvantage of many of these, such as galvanic couple sensors, resistivity sensors, and some fiber optic sensors, is that they are more properly considered corrosivity sensors; that is, they detect degradation of a sensor element and not degradation of the structure of interest. As such, they measure only how corrosive the environment is and provide no direct information on the condition of the paint coating or the structure. They can only monitor coating health if they are installed underneath the coating system. Furthermore, they are consumed and have a limited lifetime and can provide no information concerning any environmental degradation prior to installation. A second disadvantage of many sensors is that they need to be embedded into the structure. This limits them to new construction and poses important issues on the effect of the sensor on structure properties and data acquisition/transfer. These sensors cannot inspect existing structures and cannot be replaced if damaged or past their useful lifetime. The electrochemical impedance sensor approach has neither of these critical disadvantages. The technology is suitable for determining coating health from the top surface of the coating.

An innovative coating health monitoring system (CHM) consists of a series of mini-potentiostat modules coupled to two or more tape electrodes mounted on top of the paint coating of the structure or equipment being monitored. The electrodes and modules can be coated with a topcoat if desired. They periodically report to a laptop or handheld device so that an inspector can assess the condition at each sensing point. The inspector can then determine if more detailed inspection or maintenance needs to be scheduled. Communications is implemented using the Zigbee wireless protocol. The units are battery powered an estimated battery lifetime of up to ten years, depending on the frequency of measurement and interrogation. This CHM system tracks corrosion damage from its early stages, indicates an assessment of current condition, and provides a prediction of future condition based on accelerated laboratory testing. Aside from the initial installation and eventual battery replacement for the wireless units, it requires no personnel access to the monitored locations. The CHM offers several advantages over other systems:

- It directly inspects and assesses the condition of the coating of interest. It does not involve corrosivity sensors that simply detect degradation of a sensor element.

- It is applicable for both new fabrication and retrofitting existing structures. It requires no embedded sensors that must be incorporated into a structure during manufacture or refurbishment and cannot be replaced.
- It can detect the intrusion of moisture well before any irreversible corrosion damage occurs while it is also sensitive to the growth of corrosion products during the more severe stages of damage.
- The modules monitor coating health on a programmed schedule and store the results in nonvolatile memory so that the results can be retrieved later.
- The electrodes are flexible so that it can conform to edges, corners, and curved surfaces. They are corrosion resistant and have survived >1000 hours in salt fog, but can be easily replaced, if needed, or protected by paint for indefinite life.
- The area monitored by the tape sensor depends on the surface wetness so a measurement taken when the surface is wet probes a relatively large area while a measurement taken when the surface is dry is more localized around the tape. That is, the sensor monitors an area around the tape electrode and not just the protected area beneath the tape

The CHM is based on electrochemical impedance spectroscopy (EIS), a well-established laboratory technique known to predict materials performance,¹⁴⁻¹⁸ but usually limited to immersion studies. The sensor extends the use of EIS to field applications and allows identical measurements to be taken under service conditions and in the laboratory. As a coating degrades, its EIS spectrum changes as shown in Figure 1.¹⁹ The low-frequency impedance decreases by several orders of magnitude. This decrease in low-frequency impedance takes place as moisture penetrates the coating and is well before any corrosion of the substrate occurs. As a rule of thumb, coatings with low-frequency impedances greater than $10^7\Omega$ are protective and those with low-frequency impedances less than $10^7\Omega$ have poor barrier properties. The later coatings must rely on corrosion inhibitors to protect the substrate; coating systems without inhibitors will allow substrate corrosion once their barrier properties are compromised. Thus the low-frequency impedance can give early warning of decreasing coating protectiveness so that repainting/painting or other maintenance activities can be scheduled.

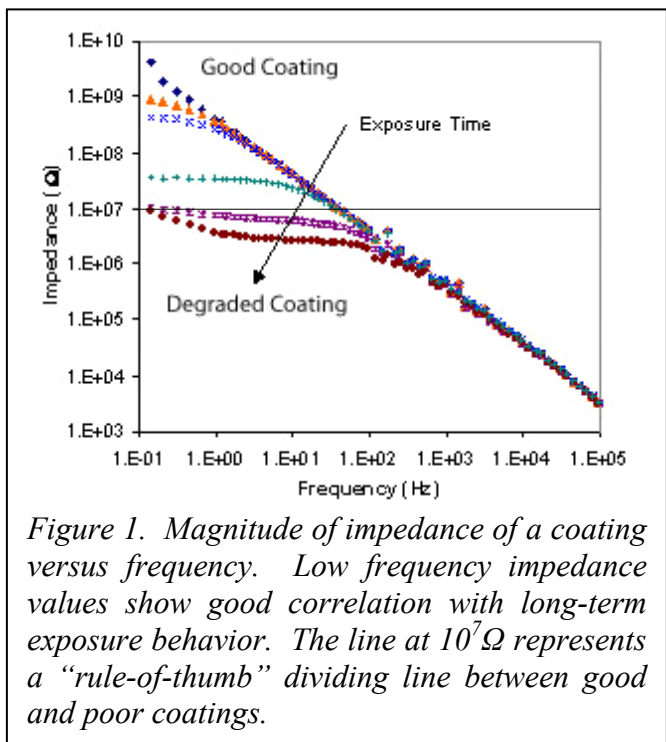
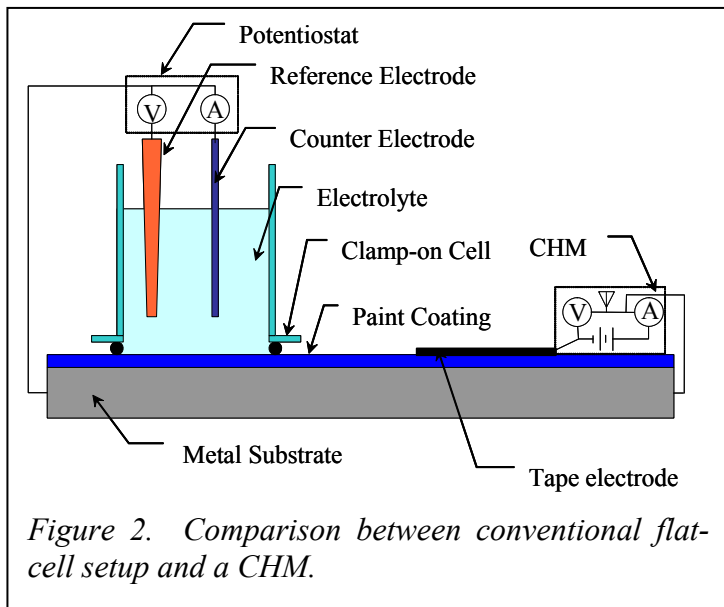


Figure 2 shows a comparison between conventional flat-cell set-up with that of the CHM. With the flat cell, a cell is sealed to a horizontal substrate and is filled with electrolyte. Counter and reference electrodes are inserted into the electrolyte. A potentiostat is then connected to take EIS measurements. With the CHM, a tape electrode is applied to the coating surface and serves as both the counter and reference electrodes. The CHM consists of a minipotentiostat, battery power supply, and transceiver to communicate with the monitoring computer. Electrical connection to the substrate is typically achieved via the mounting bolts or screws.

A major part of the CHM design was selection of components for low base current draw to maximize battery lifetime and the development of a microcontroller based single chip function generator for



digitally synthesizing cell excitation sinusoids. The function generator chip is programmable for sine wave frequency, DC offset and amplitude and produces stable output over the specified -40°C to $+85^{\circ}\text{C}$ operating temperature range of the CHM instrument. The prototype circuit draws extremely low active and sleep-mode currents and operates at 2.7 volts. These parameters will allow the instrument to operate over a long life from a battery source.

CHM wireless communication is accomplished using the Zigbee 802.15 compliant protocol. Each CHM module includes an on-board transceiver module allowing the instrument to communicate with other CHM modules or a single base module

using power efficient communications. The host module may be interfaced with a PDA (Personal Digital Assistant)-type device or other graphical user interface with a USB port.

Software for controlling and interfacing with the prototype CHM electronic circuitry was designed and constructed in the LabVIEW^a Real Time environment. This development system allows programs to be written in a graphical language. The software is then compiled into a form that can be downloaded into a hardware implementation in a Field Programmable Gate Array (FPGA). This hardware implementation allows the program to run in a fast real time environment with deterministic timing. The operation of software and algorithms designed to conduct EIS measurements was validated using prototype electronic circuitry and coated test panels with tape electrodes attached.

Potential applications of the CHM include highways, and bridges, military and civilian land vehicles, aircraft, storage tanks, pipelines, and ships. The benefits of the assessment system will become increasingly important as these systems and structures age and are not replaced. CHM devices are strategically placed on a structure in areas that are difficult to access, monitor, and maintain. These wireless remote sensors can be read from up to 500 feet away with a laptop or PDA that displays the current condition of the coating in the area of each sensor. The CHM system can be integrated into existing Condition Based Maintenance (CBM) software or used as a stand-alone system. Benefits of a CHM system include reducing inspection costs and avoiding repainting unnecessary areas. There is also an added safety benefit associated with performing fewer inspections and painting only when necessary in areas that are difficult and dangerous to access.

EXPERIMENTAL PROCEDURE

A variety of paint coatings, ranging from household paints to high-performance aerospace coatings, were used to evaluate the CHM. These coatings were chosen to represent a wide variety of corrosion protection performance ranging from coatings that fail very quickly to those that exhibit very little degradation. Each primer or topcoat was given two coats. Both cold rolled steel and aluminum substrates were coated.

^a Trademark of National Instrument Company, Austin, TX.

Because of the large number of panels and only two available CHM prototype units, only a very few panels had CHMs mounted during the testing (Figure 3). Two tape electrodes (labeled 1 and 2) were applied to the panel surface and attached to the CHM. The others had tape electrodes mounted on them (two for the 6"x12" panels and one for the 4"x6" panels) and a spare CHM module was connected via alligator clips during measurements.

Accelerated corrosion exposure was achieved with alternate immersion (10 minutes immersion and 50 minutes atmosphere) in 3.5% NaCl solution (ASTM G44)²⁰. Periodically, the CHM module was attached to panels during the dry cycle and measurements were taken. The CHM was programmed and interrogated from a laptop computer in an office 40-50 feet away.

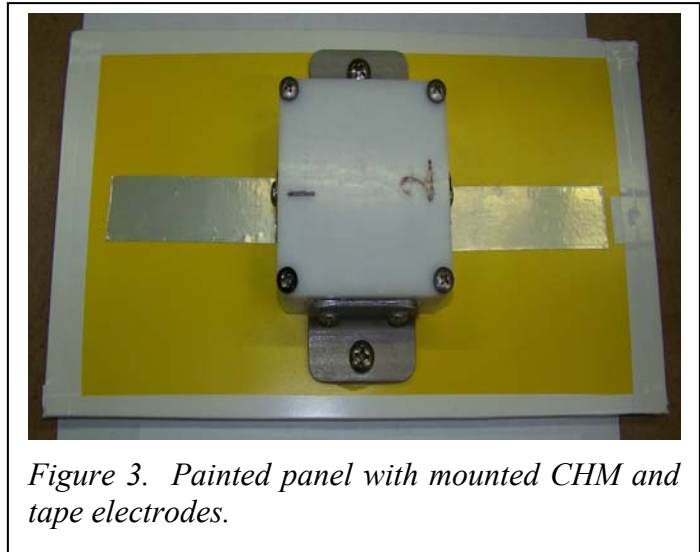


Figure 3. Painted panel with mounted CHM and tape electrodes.

To verify the accuracy of the CHM, comparisons were made using a commercial Gamry bench top potentiostat using both RC circuits and coated panels. The EIS measurements for the CHM and bench potentiostat exhibit excellent agreement over six orders of magnitude (Figure 4) for all three frequencies measured by the CHM. The scatter seen for the paint coatings likely is a result of the coatings drying out between the two sets of measurements; for the invariant RC circuits, almost no scatter is observed. To put the impedance values in perspective, a good coating system would typically exhibit an impedance of $10^8 \Omega$ or higher while a poor coating system that no longer provides a barrier to the environment would typically exhibit an impedance of $10^6 \Omega$ or lower.

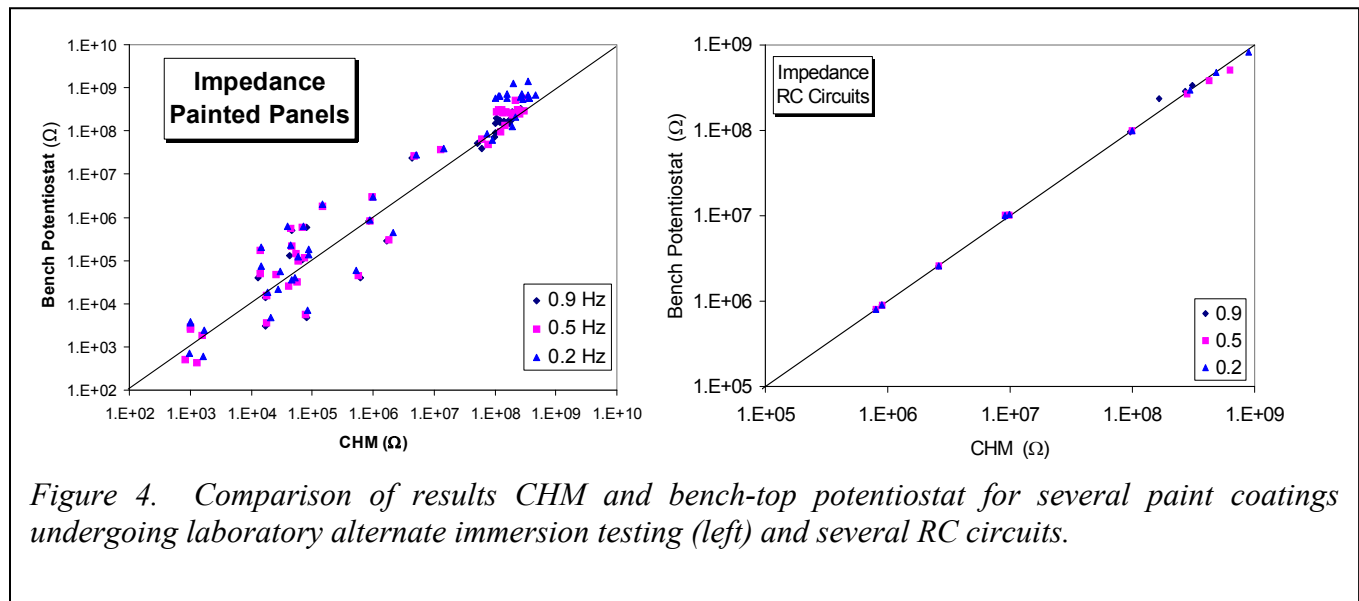


Figure 4. Comparison of results CHM and bench-top potentiostat for several paint coatings undergoing laboratory alternate immersion testing (left) and several RC circuits.

RESULTS

Examples of coatings with good and poor performance are given in Figure 5. The good coating exhibits high electrochemical impedance with very little change during the testing period. No corrosion can be seen after 36 days of testing. In contrast, although the poor coating exhibited high electrochemical

impedance before testing, its impedance had dropped by three to four orders of magnitude by the first measurement period. A further check on the condition of the coating is the impedance dispersion for the three frequencies. For the good coating, the impedances remain distinct, indicating that the low-frequency impedance spectrum has capacitive behavior. (That is, the Bode log-log plot of impedance vs frequency has a negative slope as shown in Figure 1.) For the poor coating, three impedances are nearly identical, indicating resistive behavior. (That is, the Bode plot has a near zero slope also as shown in Figure 1.) Both the CHM and Gamry bench top measurements give similar results.

In a few cases, duplicate painted panels were prepared. In one case, a CHM was mounted on one panel while a nominally identical panel was tested using the free CHM. The two panels exhibited very different EIS behavior during testing (Figure 6) with one exhibiting a slow decrease in impedance and the other exhibiting a much more rapid decrease in impedance of four to five orders of magnitude. At the end of its test (56 days), the first panel had no corrosion except at or near one corner. This corrosion appeared to originate under the tape that was intended to protect the panel edge where coating defects often occur. The second panel had a mounted CHM unit during the alternate immersion testing. Once the CHM was removed after 31 days, corrosion was apparent that had begun at a coating defect underneath the CHM module. Here the CHM detected this defect very shortly after the alternate immersion testing began.

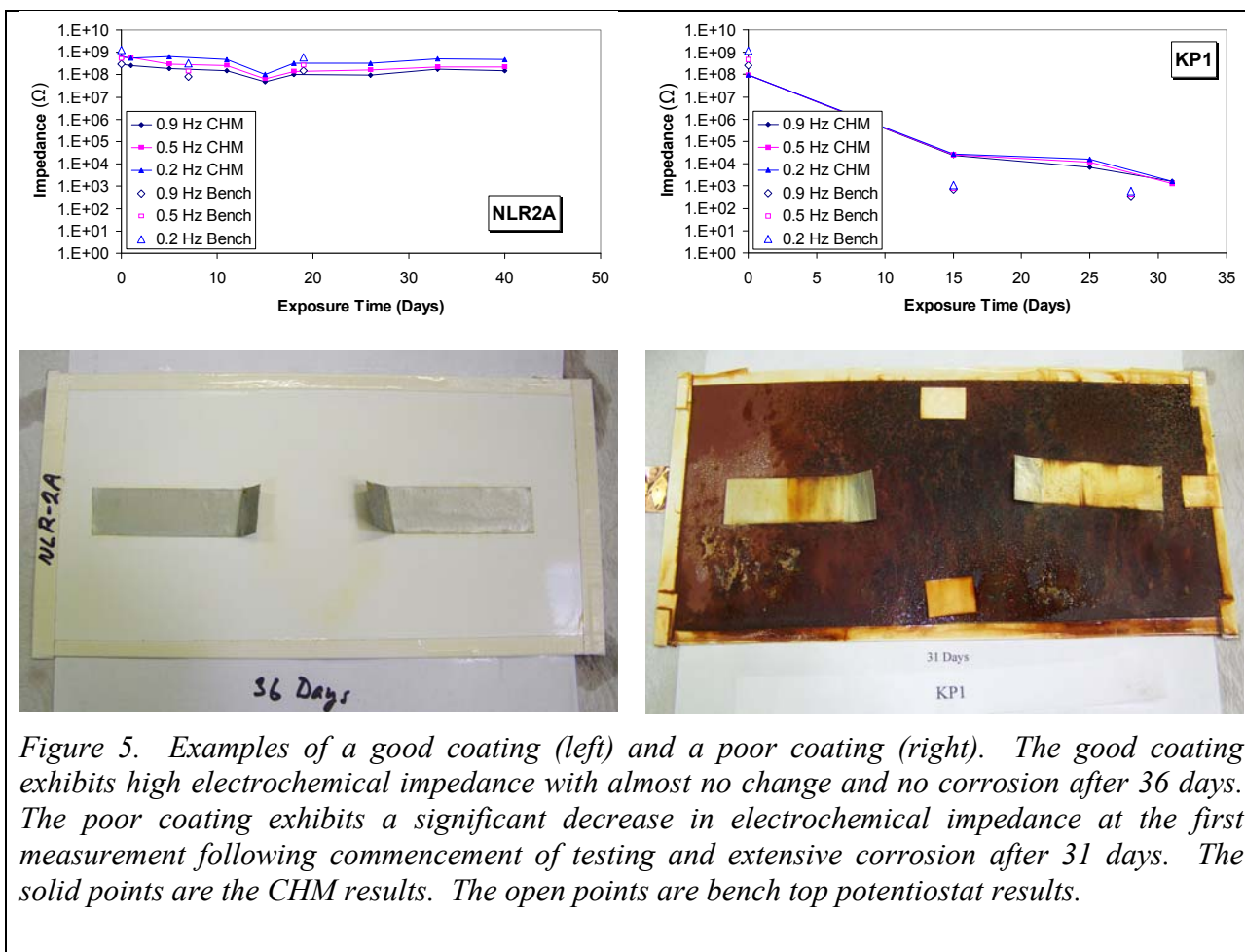


Figure 5. Examples of a good coating (left) and a poor coating (right). The good coating exhibits high electrochemical impedance with almost no change and no corrosion after 36 days. The poor coating exhibits a significant decrease in electrochemical impedance at the first measurement following commencement of testing and extensive corrosion after 31 days. The solid points are the CHM results. The open points are bench top potentiostat results.

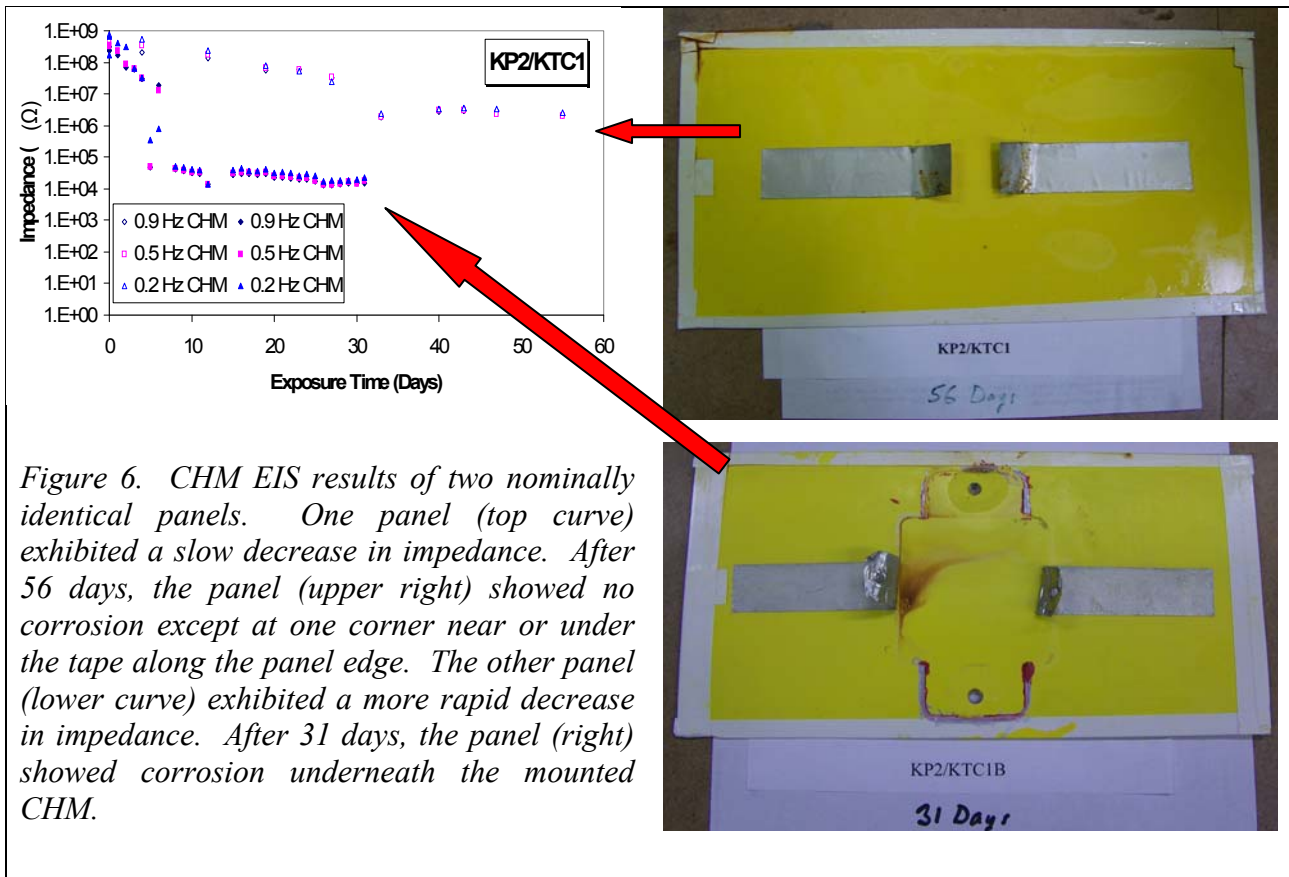


Figure 6. CHM EIS results of two nominally identical panels. One panel (top curve) exhibited a slow decrease in impedance. After 56 days, the panel (upper right) showed no corrosion except at one corner near or under the tape along the panel edge. The other panel (lower curve) exhibited a more rapid decrease in impedance. After 31 days, the panel (right) showed corrosion underneath the mounted CHM.

The spatial extent that the tape electrodes probe depends on the wetness of the surface and near-surface region of the paint. Two experiments demonstrate this. In the first, the second panel from Figure 6 was removed from the alternate immersion testing and allowed to dry thoroughly under ambient conditions while measurements were taken. The results are shown in Figure 7. The results illustrate two points: As the surface or surface region of the paint dries, the detection range of the tape electrodes decreases (becomes more localized) as the electrical resistivity of the surface increases and possible surface conduction paths are eliminated. Sensor #1, represented by the solid symbols, was the tape away from the corroding spot, that is, it was the right-most electrode of Figure 6. It detects the corrosion initially, but as the surface dries; its area of detection shrinks and it no longer sees the defect. Sensor #2 was closer to the corroding area, that is, the left-most electrode of Figure 6, and detects the corrosion for a longer time. Because at least part of surface conduction path is underneath the CHM module, drying proceeds more slowly so the transition between detection and no detection occurs more gradually.

Another way to show the increased detection area when the surface is wet is to discuss the results of one of the aerospace coated panels. These panels were coated on only the front surface. The edges and back were masked with tape, but the masking is not complete. Initially, the CHM measurements were begun shortly after the immersion portion of the testing cycle. Low impedance values were seen for several panels even though the coatings were expected

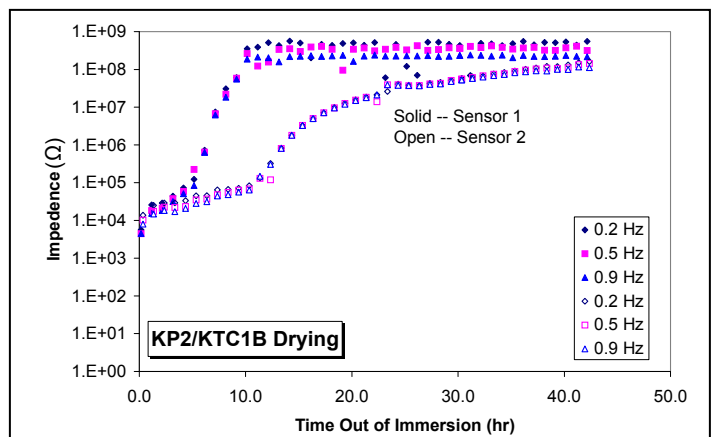


Figure 7. Second panel from Figure 6 after removing from alternate immersion testing.

to be good. It was noted that measurements of electrode tape #2 were generally higher than those of electrode tape #1 that were taken first. To determine if the drying process was causing erratic results, a panel was measured shortly after emersion and then after approximately one hour. Figure 8 shows the results: when the panel was wet, the EIS measurements detected the edge or edge defects; when it was dry, they did not. To improve consistency, it was decided to allow the panels to dry under ambient conditions for ten minutes before beginning measurements.

In the field, this variability in detection range can be used to advantage, if the degree of wetness is known. When the surface is wet, the CHM will be monitoring a larger area; when the surface is dry, it will be monitoring a smaller area.

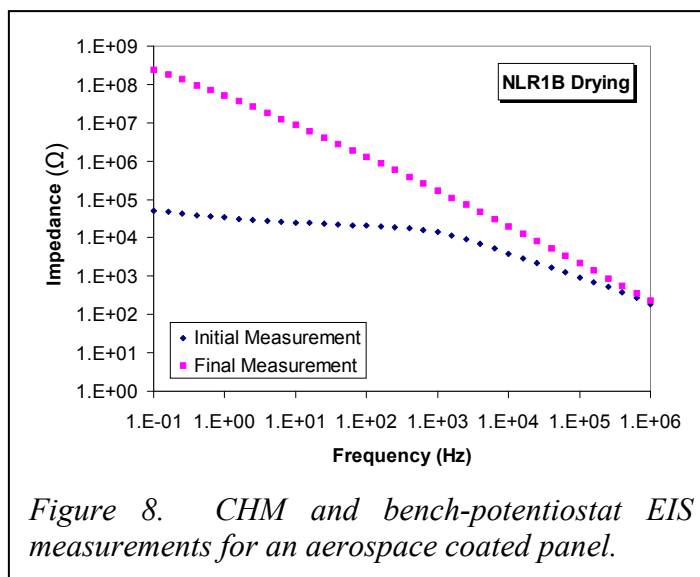


Figure 8. CHM and bench-potentiostat EIS measurements for an aerospace coated panel.

CONCLUSIONS

A coating health monitor has been fabricated and tested. It acquires EIS measurements at three frequencies that compare well to those from commercial bench-top potentiostats over several orders of impedance magnitude. The CHM enclosure and tape electrodes survive months of alternate immersion testing in salt water. Wireless communication can be routinely achieved at an office-to-laboratory distance of 10-15 meters. The CHM measurements successfully detect both coating degradation and coating defects. The area that the CHM monitors the coating health depends on the surface wetness.

ACKNOWLEDGMENTS

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